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ABSTRACT

In this study errors of the relative orientations of polarizers in the Cimel polarized sun-sky radiometers are measured and introduced into the Mueller matrix of the instrument. The linearly polarized light with different polarization directions from 0° to 180° (or 360°) is generated by using a rotating linear polarizer in front of an integrating sphere. Through measuring the referential linearly polarized light, the errors of relative orientations of polarizers are determined. The efficiencies of the polarizers are obtained simultaneously. By taking the error of relative orientation into consideration in the Mueller matrix, the accuracies of the calculated Stokes parameters, the degree of linear polarization, and the angle of polarization are remarkably improved. The method may also apply to other polarization instruments of similar types.

1. Introduction

Polarization is one of inherent properties of light. It is commonly described by the Stokes vector [1]. The linearly polarized components of the Stokes vector *I*, *Q*, and *U* are usually determined from total radiance measurements with three polarizers in different orientations [2,3]. The Dual-Polar sun-sky radiometer CE318-DP produced by the Cimel Electronique is an advanced, ground-based polarimetric radiometer that has been deployed in the AErosol RObotic NETwork (AERONET) and the Sun-sky radiometer Observation NETwork (SONET) to measure linear polarization of skylight [4,5].

The CE318-DP design consists of two rotating wheels (i.e., a polarizer wheel and a filter wheel) assembling nine polarizers and nine filters, respectively. As the key polarization elements, the nine polarizers are divided into three sets of triplets. Each triplet consists of three polarizers. The polarimetric measurements at each channel are performed by using the three rotating polarizers in front of a same spectral filter. The exact relative orientations of three polarizers are crucial in the calculations of the Stokes parameters *I*, *Q*, *U*, as well as the degree of linear polarization *DoLP* and the angle of polarization *AoP* [6,7]. The influence of relative orientations feeds into the Mueller matrix. Thus, measurement of the relative orientations of polarizers should already be considered in the polarization calibration. The spaceborne polarization instruments including POLDER-1 (POLarization and Directionality of the Earth's Reflectances)/ADEOS-1, POLDER-2/ADEOS-2, POLDER/PARASOL, DPC (Directional Polarimetric Camera)/GF-5, and CAPI (Cloud and Aerosol Polarimetric Imager)/TanSat had all taken the relative orientations of polarizers into consideration in their pre-flight calibrations [6,8,9]. However, the ground-based CE318-DP, which is usually used to validate the satellite measurements, has not considered the relative orientation angles so far. To the polarized sun-sky radiometer, calibration of the efficiencies of the polarizers and the difference between the responses for two of the three polarizers have been suggested in previous studies [10,11]. Nonetheless, the polarization parameters *I*, *Q*, *U*, *DoLP*, and *AoP* are all determined with the hypothesis that the relative orientation angle is exactly equal to 60° for any two of the three polarizers [3,5,11]. Errors in the relative orientation angles between the polarizers are inevitable due to imperfect installation and rotating position error. That might imply errors in the polarimetric mea-

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surements using the CE318-DP, which are systematically studied in this paper.

To cope with this problem, the orientations of polarizers for CE318-DP are measured by using rotating linearly polarized light as reference. However, the relative orientations are not determined through the difference between the minimum (or maximum) of the sinusoid fitting of the instrument signals, in consideration of the large uncertainties for the absolute positions of the minimum (or maximum) [6,8]. Instead, a new method, which simultaneously determines the relative orientations and efficiencies of the polarizers, is developed in this study. Furthermore, the impacts of errors of the relative orientations on the calculations of the Stokes parameters, the degree of linear polarization, and the angle of polarization are also discussed. This work can help to improve the accuracy of polarization parameter measurements for the sun-sky radiometer.

2. Methodology

2.1. Radiometric model

The radiometric model of the polarized sun-sky radiometer quantifies the response of the detector with respect to any input polarized light in each spectral channel [6,7,12]. The interaction of an incident polarized beam with a polarizing element (e.g., atmospheric particle, optical instrument) is described by the Mueller matrix. The CE318-DP is equipped with lens, linear polarizer, filter and detector. Interactions of the incoming light with these optical elements are described by the Mueller matrix of instrument by the relations [1]:

$$\vec{S'} = \mathbf{M} \cdot \vec{S}, \tag{1}$$

where $\vec{S}$ is the Stokes vector of the incident light and $\vec{S'}$ is the Stokes vector of the light beam after interactions with lens, polarizer, and filter then be received by detector. **M** is a 4×4 matrix known as the Mueller matrix of the instrument, which can be expressed as:

$$\mathbf{M} = T \begin{bmatrix} 1 & \eta \cos 2(\varphi - \alpha) & \eta \sin 2(\varphi - \alpha) & 0 \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix}, \tag{2}$$

with the efficiency of the polarizer $\eta = (k_1 - k_2)/(k_1 + k_2)$ [7]. k_1 and k_2 are transmittances of the linear polarizer along the preferred axis and along an axis of 90° with respect to the preferred axis. φ indicates the desired orientation angle of polarizer (e.g., 0°, 60°, or 120°). α represents the error angle of the relative orientation for two of the three polarizers. The Stokes vectors refer to the coordinate system, which is based on the instrument frame with the plane containing the direction of 0° polarizer-preferred transmission axis and the direction of propagation of light as reference [3]. The coefficient T refers to transmissions of the lens, filter, and linear polarizer. Polarization of the optics can be neglected, considering that the field of view is only 1.3° for the CE318-DP and the stress birefringence in the lens can also be ignored owing to application of the low stress assembly technology [7,13]. The elements of the Mueller matrix $m_{ij}(i=2,\ 3,\ 4;\ j=1,\ 2,\ 3,\ 4)$ are not specified because only the first row of the matrix is important for total radiance measurements.

The relative orientation for any two of the three polarizers is supposed to be 60°. For simplicity, we assume the desired orientations of the three polarizers P_1, P_2, and P_3 as 0°, 60°, and 120° with P_1 defining as the 0° polarizer. The error angles of relative orientations, which are imported through the imperfect installation of the polarizers and the rotating process, should be rigorously measured. For each spectral band, three radiance measurements corresponding to the three orientations of linear polarizers are sufficient to characterize the Stokes parameters I, Q, and U of the incident light [7]:

$$\begin{pmatrix} I \\ Q \\ U \end{pmatrix} = \begin{pmatrix} 1 & \eta_1 \cos 2(\varphi_1 - \alpha_1) & \eta_1 \sin 2(\varphi_1 - \alpha_1) \\ 1 & \eta_2 \cos 2(\varphi_2 - \alpha_2) & \eta_2 \sin 2(\varphi_2 - \alpha_2) \\ 1 & \eta_3 \cos 2(\varphi_3 - \alpha_3) & \eta_3 \sin 2(\varphi_3 - \alpha_3) \end{pmatrix}^{-1} \begin{pmatrix} C_1 \cdot N_1 \\ C_2 \cdot N_2 \\ C_3 \cdot N_3 \end{pmatrix}, \tag{3}$$

where I, Q, and U denote the first three components of the Stokes vector $\vec{S}$. N_1, N_2, and N_3 are the digital numbers measured at three orientations. C_1, C_2, and C_3 indicate the absolute calibration coefficients for a polarized channel, which are applied to convert the instrumental output signal into radiance [7]. The coefficients α_1, α_2, α_3, η_1, η_2, η_3, C_1, C_2, and C_3 correspond to the three polarizers in each spectral channel. $\varphi_1 = 0°$, $\varphi_2 = 60°$, and $\varphi_3 = 120°$. $\alpha_1 = 0°$ because P_1 is defined as the 0° polarizer. Like the absolute radiance calibration for the non-polarized channel, the absolute calibration coefficients for the polarized channel C_1, C_2, and C_3 are easily obtained by measuring unpolarized reference light from an integrating sphere [3]. The measurements of α_2, α_3, η_1, η_2, and η_3 remain difficult. To deal with this problem, a rotating linearly polarized light beam is used as incident reference light. It can be expressed as:

$$\vec{S} = \begin{bmatrix} I \\ Q \\ U \end{bmatrix} = \begin{bmatrix} I \\ I \cdot \cos 2\chi \\ I \cdot \sin 2\chi \end{bmatrix}, \tag{4}$$

where χ incidents the angle of polarization of the incident light that is defined with respect to the reference plane in the instrument frame. χ varies from 0° to 180°. Substituting Eq. (4) into Eq. (3) to yields:

$$\begin{aligned} N &= \frac{I}{C}[1 + \eta \cdot \cos 2\chi \cdot \cos 2(\varphi - \alpha) + \eta \cdot \sin 2\chi \cdot \sin 2(\varphi - \alpha)] \\ &= \frac{I}{C} + \frac{I}{C} \cdot \eta \cdot \cos 2[\chi - (\varphi - \alpha)]. \end{aligned} \tag{5}$$

Then Eq. (5) can be transformed into:

$$N = y_0 + A \cdot \cos \pi \frac{\chi - \chi_c}{w}, \tag{6}$$

where $y_0 = I/C$, and $A = \eta \cdot I/C$. w is half cycle. The value of w is close to 90°. χ_c is the relative orientation of polarizer. The error angles of the relative orientations of P_2 and P_3 with respect to P_1 are obtained by:

$$\alpha_2 = 60° - (\chi_{c1} - \chi_{c2}), \tag{7}$$

$$\alpha_3 = 120° - (\chi_{c1} - \chi_{c3}) \text{ or } \alpha_3 = -60° - (\chi_{c1} - \chi_{c3}). \tag{8}$$

In this way the coefficients α_1, α_2, α_3, η_1, η_2, η_3, C_1, C_2, and C_3 are all attained. Substituting them into Eq. (3) gives the results of the Stokes parameters I, Q, and U. Then, the degree of linear polarization $DoLP$ and the angle of polarization AoP can be calculated by:

$$DoLP = \frac{\sqrt{Q^2 + U^2}}{I},\ 0 \le DoLP \le 1, \tag{9}$$

$$\chi = \frac{1}{2} \operatorname{atan} \frac{U}{Q},\ 0 \le \chi < \pi. \tag{10}$$

2.2. Measurement of relative orientations of polarizers

Laboratory experiments were conducted to measure the relative orientations and efficiencies of the polarizers for the CE318-DP #0966 and #0974. Then data were taken to test the consistency

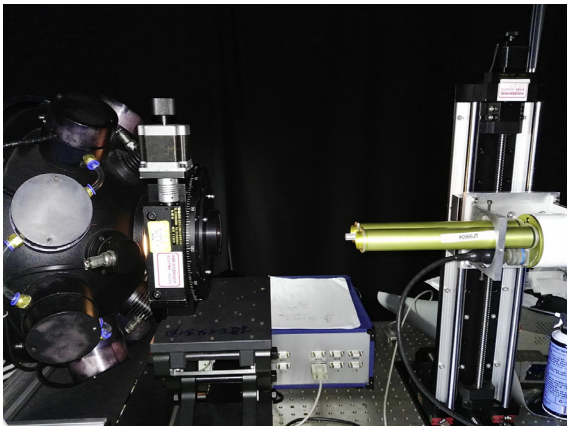

Fig. 1. Experimental set up for measurement of relative orientations of polarizers for the polarized sun-sky radiometer CE318-DP.

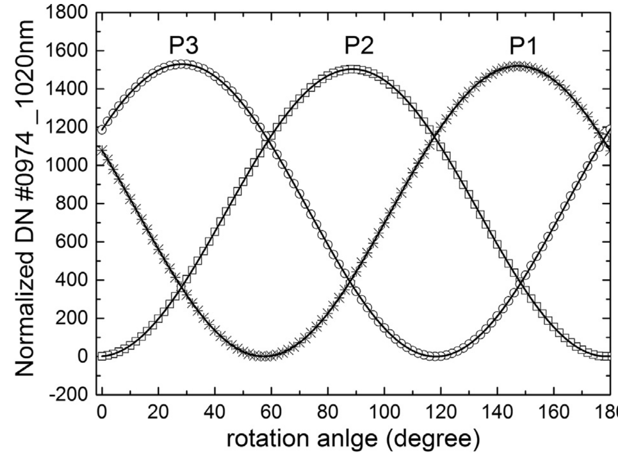

Fig. 2. Fitting of the normalized digital number curves for the three polarized channels P_1, P_2, and P_3 of the CE318-DP.

of the results of relative orientations for the CE318-DP #0966. The experimental set up is illustrated in Fig. 1. As the referential light source system, a rotating linear polarizer was placed in front of an integrating sphere. The integrating sphere STIS250-80 was manufactured by the Anhui Institute of Optics and Fine Mechanics (AIOFM), Chinese Academy of Sciences (CAS). The sphere diameter is 250 mm and the exit port diameter is 80 mm. The STIS250-80 is designed with 4 halogen lamps and 8 light-emitting diode (LED) modules. Radiometric calibration for the integrating sphere was based on the standard lamb of the National Institute of Metrology (NIM), China. The referential linear polarizer is an extremely broadband OWL (Outrageously Wide Lambda) polarizer [14]. The polarizer has excellent transmitted contrast in the wavelength range from 300 nm to 2700 nm. The dimension of the polarizer is 50.8 mm. This light source system yielded linearly polarized light with different polarization orientations. The linear polarizer rotated from 0° to 180° (or 360°) with an interval of 2°. For the referential polarizer, the 0° direction is not rigidly fixed. The preferred transmission axis of the linear polarizer along the vertical direction was set as 0° for convenience. The CE318-DP performed measurements in all unpolarized and polarized channels for each rotation of the referential polarizer.

The output from the integrating sphere was not sustained during the period of measurement. The total radiance changed gradually, resulting in unequal amplitudes for the digital number curves of three polarizers. Therefore, the raw data were normalized to the initial digital number of the corresponding unpolarized channel in the 0° direction. Moreover, the gains were generally amplified in actual measurements to make sure that the ranges of digital numbers in the polarized channels were not too limited. A relative gain coefficient was calculated by the actual and the original gains for each polarized channel. Then, the normalized digital numbers were adjusted by corresponding relative gain coefficients.

After preprocessing, the normalized digital number curves corresponding to the three polarized channels P_1, P_2, and P_3 were fitted by the sinusoids (or cosinusoids) with the formula of Eq. (6), see Fig. 2. Thus, the relative orientations and efficiencies for the three polarizers in each channel were obtained.

3. Results

The 0° polarizer was changed to P_2 in order to keep consistency with the previous method [3]. The measured coefficients of the polarized channels at 1020 nm and 870 nm wavelengths for the CE318-DP #0966 and #0974 are listed in Table1. It is evident that the absolute error angles of the relative orientations are less than 0.99° for the CE318-DP #0966 and less than 1.42° for the CE318-DP #0974. Our previous study has illustrated that the channels centered at 1020 nm and 870 nm share the same set of polarizer triplet [3]. From Table 1, it is also concluded that the corresponding error angles of the relative orientations for the channels of 1020 nm and 870 nm of the same instrument are close to each other. The differences between these two channels are merely about 0.02°–0.07°. The efficiencies of the polarizers are all greater than 99.8%. Nevertheless, some values greater than the theoretical upper bound of 100% can also be found for the CE318-DP #0974. A reasonable explanation for the overflowing efficiencies is systematic uncertainties including the black measurements and intensity fluctuations of the light emerging from the integrating sphere [15]. They changed the digital numbers subtly and might lead to A slightly greater than y_0. In this situation, efficiency of the polarizer is fixed at 100%, which would not cause significant bias in the calculations of the Stokes parameters.

Results of the Stokes parameters *I, Q, U, DoLP* and *AoP* calculated with the coefficients of the CE318-DP #0966 and #0974 are shown in Figs. 3 and 4. The corresponding results not taking into account the errors of relative orientations α are also illustrated. It appears that I calculated considering α are consistent with the total radiance measured in the corresponding unpolarized channels, see Figs. 3(a and b) and 4(a and b). The differences are generally within ±0.2%. However, the differences between I without considering α and the corresponding unpolarized measurements attain to ±1.6%. They present obvious systematic change with the rotation angle, which imply there are still some factors having influences on the calculation of I, while this systematic change is removed after accounting for α. For Q in Figs. 3(c and d) and 4(c and d), $\Delta Q/I$ with and without considering α are within ±1% for the CE318-DP #0966 and within ±1.5% for the CE318-DP #0974. Correspondingly, $\Delta U/I$ with and without considering α are within ±2.4% for the CE318-DP #0966 and within ±3.5% for the CE318-DP #0974, see Figs. 3(e and f) and 4(e and f). $\Delta Q/I$ and $\Delta U/I$ all change regularly with the rotation angle. It indicates that the error of relative orientation has obvious influence on the Stokes parameters Q and U. The results of *DoLP* calculated with considering α are closer to the theoretical value than those without considering α, see Figs. 3(g and h) and 4(g and h). The results of *DoLP* are greatly improved from a standard deviation of ±0.0104 to ±0.002 in the 1020 nm channel, and from ±0.0107 to ±0.0011 in the 870 nm channel before and after considering α for the CE318-DP #0966. The latter is close to the calibrated results for other polarimetric instruments [16,17]. For the CE318-DP #0974, the standard deviation of *DoLP* are also im-

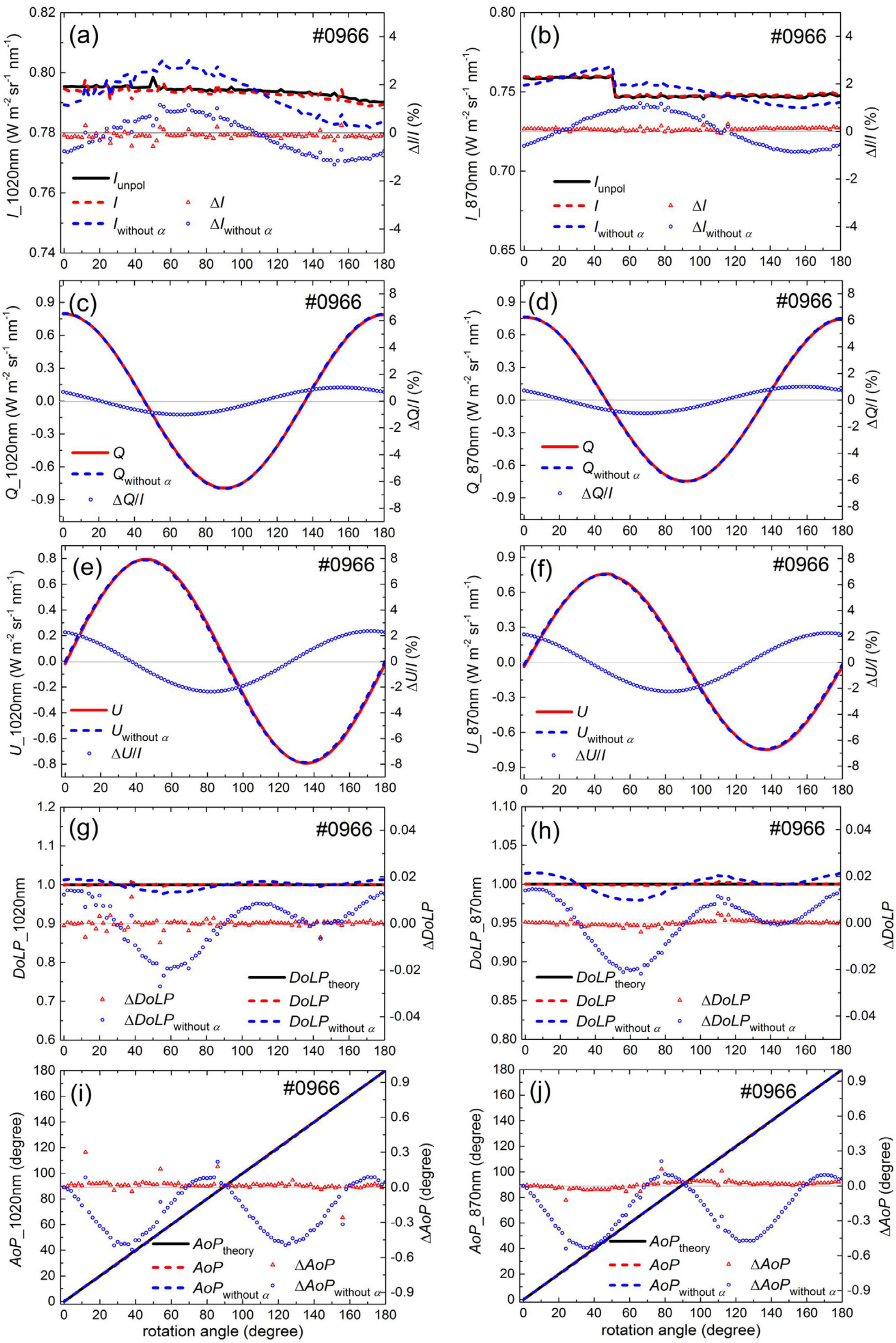

Fig. 3. Results of the Stokes parameters *I* (a,b), *Q* (c,d), *U* (e,f), the degree of linear polarization *DoLP* (g,h) and the anlge of polarization *AoP* (i,j) for the CE318-DP #0966 calculated with or without considering errors of the relative orientations of polarizers α.

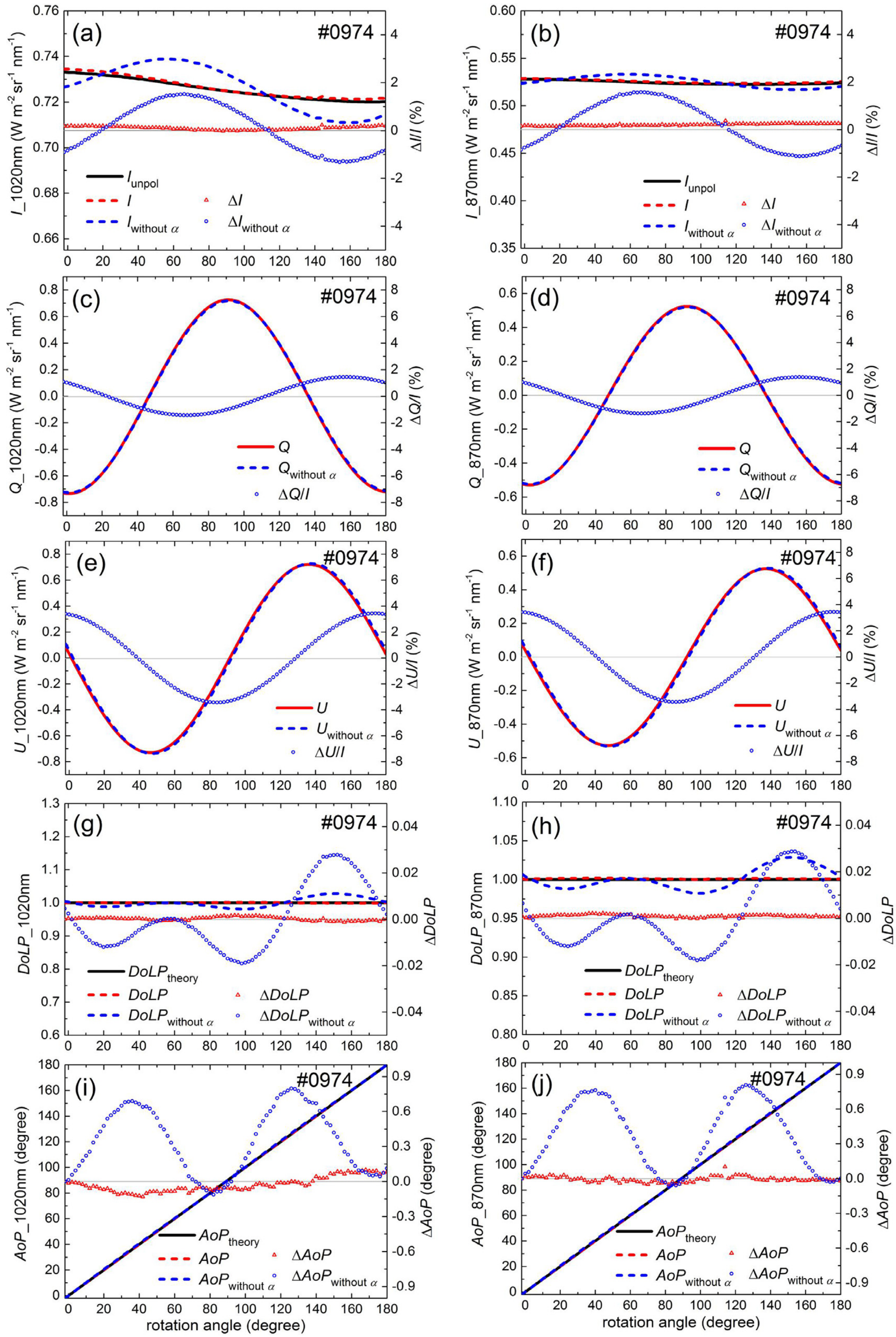

Fig. 4. Same as in Fig. 3, but for the CE318-DP #0974.

Table 1
The calibration coefficients for the polarized channels of the CE318-DP #0966 and #0974.

Parameter	#0966		#0974	
	1020 nm	870 nm	1020 nm	870 nm
α_1	0°	0°	0°	0°
α_2	0.320°(±0.03°)	0.273°(±0.02°)	-0.470°(±0.01°)	-0.541°(±0.01°)
α_3	0.982°(±0.03°)	0.957°(±0.02°)	-1.412°(±0.01°)	-1.365°(±0.004°)
η_1	99.99%(±0.02%)	99.89%(±0.02%)	99.89%(±0.01%)	100.07%(±0.01%)
η_2	99.91%(±0.03%)	99.88%(±0.01%)	100.02%(±0.01%)	100.15%(±0.01%)
η_3	99.97%(±0.05%)	99.94%(±0.02%)	99.90%(±0.01%)	100.09%(±0.01%)
C_1	1.206E−04	9.494E−05	1.208E−04	9.600E−05
C_2	1.207E−04	9.484E−05	1.220E−04	9.721E−05
C_3	1.203E−04	9.440E−05	1.200E−04	9.566E−05

proved from ±0.0139 to ±0.0007 in the 1020 nm channel, and from ±0.014 to ±0.0005 in the 870 nm channel. The mean absolute differences are about 0.01 for *DoLP* calculated without considering α, while they are less than 0.001 for *DoLP* calculated taking into account α. The mean absolute differences have been reduced by 10 times if taking account of the error of relative orientation in polarization calculation. From Figs. 3(i and j) and 4(i and j), it seems that the results of *AoP* calculated with and without considering α are all aligned with the theoretical value. Nevertheless, it should be noted that the absolute differences may reach up to 0.8° and appear obviously systematic change for the results without taking α into consideration. However, the mean absolute differences are only less than 0.06° for the results calculated with consideration of α. And, at the same time, they show no systematic variation. The results in Figs. 3 and 4 illustrate that α has a remarkable impact on the calculations of *I, Q, U, DoLP*, and *AoP*. Therefore, the error of relative orientation should be considered in polarization calculation for the CE318-DP.

4. Discussion

There are some factors possibly affecting the measurements. The rotation error for the referential linear polarizer should be taken into account first. In the laboratory measurements, the referential linear polarizer was fixed on a rotary table. The rotation angle of the linear polarizer was controlled by it. The angular resolution of the rotary table is 0.0002° and the repeated positioning precision is less than 0.004°. The error of rotation angle of the referential linear polarizer is quite small that leads to a tiny deviation from 90° (e.g., 90.0046°, 89.9821°) for *w*. But it has no obvious influence on the results of the relative orientations.

As mentioned above, the systematic uncertainties including the black measurements and intensity fluctuations of the integrating sphere, as well as the efficiency of the referential linear polarizer have subtle influences on the determination of efficiency of polarizer. From Table 1, the worst case occurs in the 870 nm channel for the CE318-DP #0974 with efficiency of the polarizer is 0.15% greater than the theoretical upper bound of 100%. Combined with 0.2% of the efficiency of the referential linear polarizer, uncertainty of the worst-case value of η is 0.35%. Assuming identical uncertainties of η for the three polarizers, it will result in relative uncertainties of 0.22%, 0.3%, and 0.26% for the Stokes parameters $\Delta I/I$, $\Delta Q/I$, and $\Delta U/I$, see Appendix A [18]. These variations are far less than the maximum differences with and without considering α, see Figs. 3 and 4.

The major contributors to the uncertainty of relative orientation are the initial angle errors induced by installation of the polarizers on a polarizer wheel and the positioning error of polarizer during polarization measurement process. To discuss their influences on the relative orientation, the consistency of errors of the relative orientations of polarizers α for the CE318-DP #0966 was tested in

Table 2
Errors of the relative orientations of polarizers for the CE318-DP #0966 measured on 13 and 14 October 2016.

Parameter		13 October 2016	14 October 2016	Difference
α_2	1020 nm	0.320°	0.268°	0.051°
	870 nm	0.273°	0.268°	0.005°
α_3	1020 nm	0.982°	1.025°	-0.043°
	870 nm	0.957°	1.003°	-0.046°

two experiments, see Table 2. It is evident that the maximum difference of α between the two experiments is only about 0.051°.

When considering both independent errors of η and α as the worst-case values (i.e., identical uncertainties 0.35% for η and 0.051° for α), the relative uncertainties of calculated Stokes parameters $\Delta I/I$, $\Delta Q/I$, and $\Delta U/I$ are 0.3%, 0.38%, and 0.39%, respectively (see Appendix A).

Fig. 5 illustrates the comparisons of *I, Q, U, DoLP* and *AoP* calculated by the coefficients of the two experiments. It is clear that no distinct differences in the results calculated by the two sets of coefficients. The differences between the two situations are within ±0.1% in the 1020 nm channel and within ±0.08% in the 870 nm channel for the total radiance *I*, see Fig. 5(a and b). From Fig. 5(c and d), $\Delta Q/I$ are within ±0.07% in the 1020 nm channel and within ±0.13% in the 870 nm channel. While from Fig. 5(e and f), $\Delta U/I$ are within ±0.26% in the 1020 nm channel and within ±0.04% in the 870 nm channel. For *DoLP* in Fig. 5(g and h), the mean absolute differences are 0.0015 and 0.001 and the maximum absolute differences are up to 0.003 and 0.002 in the 1020 nm and 870 nm channels, respectively. The maximum angular differences are only 0.05° and 0.015° in the 1020 nm and 870 nm channels, see Fig. 5(i and j). The feature of the angular dependences of the differences for these results indicates the influence of different α measured on 13 and 14 October 2016. Nevertheless, the results of *I, DoLP* and *AoP* calculated by the two sets of coefficients suggest that they all agree well with the unpolarized measurements or the theoretical values. It is evident that the errors of relative orientations determined by this method are consistent and can be reliably applied in polarization measurements.

Moreover, the Stokes parameters *Q, U*, and the angle of polarization vary with definition of the reference plane [3]. All of the calibrated results refer to the coordinate system in the instrument frame in this study. However, the sky frame with refer to the local meridian plane that contains the view and zenith directions is commonly adopted in polarization measurements and radiative transfer simulations. Transformation of the reference coordinate system from the instrument frame to the sky frame is related to the angle between the meridian plane and the plane containing the direction of 0° polarizer-preferred transmission axis and the direction of propagation of light. It will be affected by non-ideal installation of the optical head to the arm of the automated mount of the CE318-DP [3].

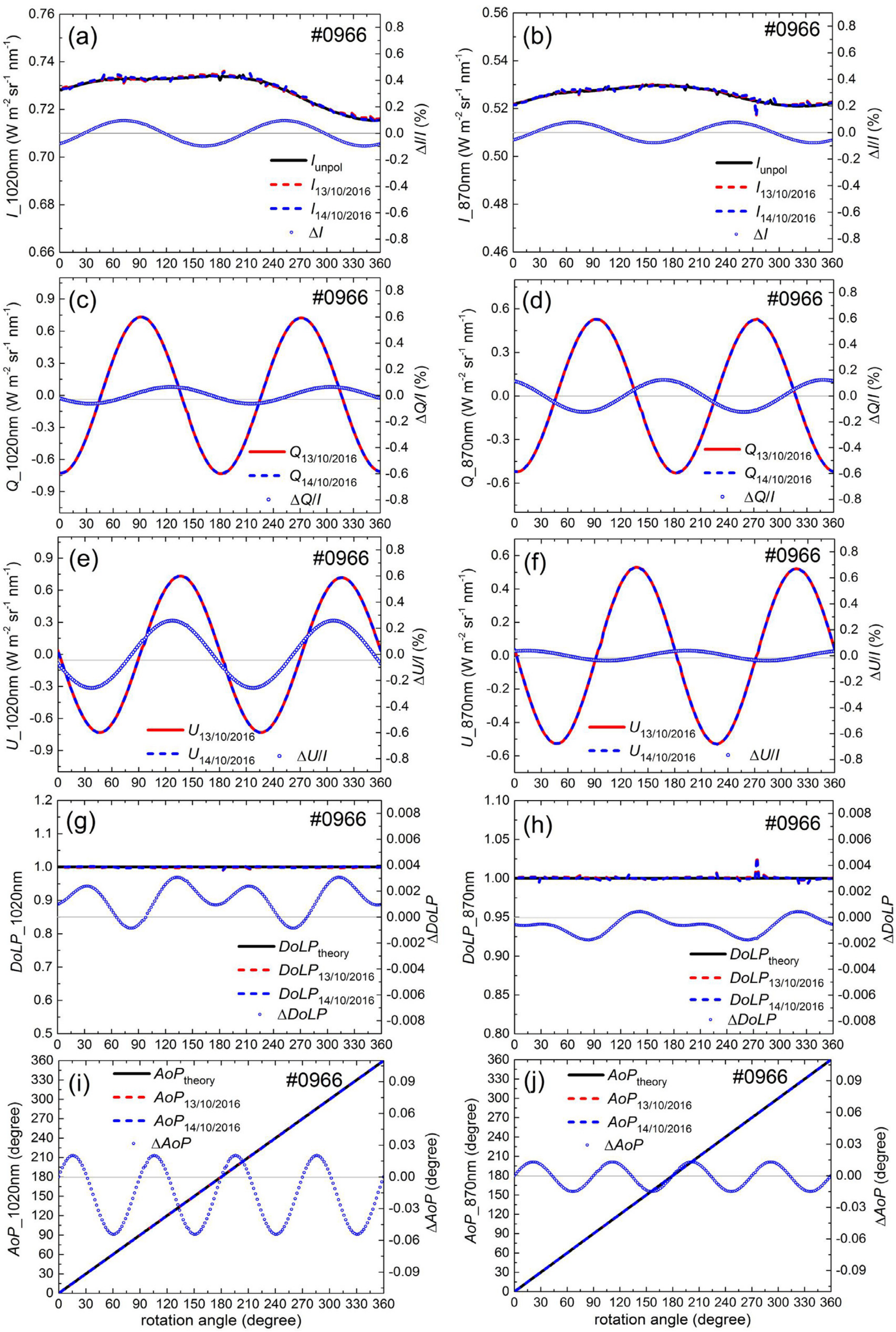

Fig. 5. Comparisons of I (a,b), Q (c,d), U (e,f), $DoLP$ (g,h) and AoP (i,j) for the CE318-DP #0966 calculated with the coefficients measured on 13 and 14 October 2016.

5. Conclusions

The polarized sun-sky radiometer CE318-DP has been widely used to measure skylight polarization for aerosol study. As a major result of this study it is concluded that errors of relative orientations of polarizers have a significant influence on the calculations of the Stokes parameters *I, Q, U*, the degree of linear polarization, and the angle of polarization from CE318-DP polarization measurements. To date this problem has been ignored in determination of the Mueller matrix of instrument in the polarization calibration process. This paper has described a new method to quantify the errors of relative orientations of the polarizers for the polarized sun-sky radiometer. The efficiency of polarizer can also be attained simultaneously. This method is easy to implement by measuring only with a rotating linear polarizer in front of an integrating sphere. After taking the error of relative orientation into consideration, the accuracies of the calculated polarization parameters are remarkably increased. More importantly, the systematic deviations are removed after accounting for the error of relative orientation. The consistency of the calibrated errors of relative orientations is validated.

It also should be noted that the sequential polarization measurements are adopted by the CE318-DP. A group of P_1, P_2, P_3 measurements takes about 3 s. The actual accuracy of the polarization calculation will also be slightly degradative due to the temporal variation of the sky during the time interval. Since the LED was used as light source in visible wave bands for the integrating sphere in the present experiments, the output intensity is not stable for the LED light source which leads to tremulous digital number curves in the channels of 440 nm, 500 nm, and 675 nm. Meanwhile, the output intensities of the integrating sphere are too low in the channels of 340 nm and 380 nm. Hence, the light source in ultraviolet and visible bands should be improved.

Acknowledgments

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Appendix A. Uncertainties of the Stokes parameters

For the Cimel sun–sky radiometers, the radiance measurements corresponding to the three orientations of linear polarizers can be calculated as [7]:

$$\begin{pmatrix} I'(0^\circ) \\ I'(60^\circ) \\ I'(120^\circ) \end{pmatrix} = \mathbf{M}_\mathrm{p} \begin{pmatrix} I \\ Q \\ U \end{pmatrix} = T \begin{pmatrix} 1 & \eta_1 \cos 2(0^\circ - \alpha_1) & \eta_1 \sin 2(0^\circ - \alpha_1) \\ 1 & \eta_2 \cos 2(60^\circ - \alpha_2) & \eta_2 \sin 2(60^\circ - \alpha_2) \\ 1 & \eta_3 \cos 2(120^\circ - \alpha_3) & \eta_3 \sin 2(120^\circ - \alpha_3) \end{pmatrix} \times \begin{pmatrix} I \\ Q \\ U \end{pmatrix}. \tag{A1}$$

The coefficient T refers to transmissions of the lens, filter, and linear polarizer. The coefficients α_1, α_2, α_3, η_1, η_2, η_3 are corresponding calibrated errors of relative orientations and the efficiencies of the three polarizers P_1, P_2, and P_3. The uncertainties of the calculated Stokes parameters *I, Q, U* can be estimated by using the error propagation rules. We define the uncertainties of the calibrated efficiencies of the polarizers η_1, η_2, and η_3 as f_1, f_2, and f_3. The uncertainties of the calibrated errors of relative orientations α_1, α_2, and α_3 are e_1, e_2, and e_3, respectively. We have $\alpha_1 = 0^\circ$ and $e_1 = 0^\circ$ when P_1 is defined as the 0° polarizer. Assuming independent errors between η and α, then the differences between the expected and observed signals are [18]

$$\begin{aligned} \Delta_{\eta 0} &= \left| I'_{(\eta_1 - f_1)}(0^\circ) - I'(0^\circ) \right| \\ \Delta_{\eta 60} &= \left| I'_{(\eta_2 - f_2)}(60^\circ) - I'(60^\circ) \right| \\ \Delta_{\eta 120} &= \left| I'_{(\eta_3 - f_3)}(120^\circ) - I'(120^\circ) \right|, \end{aligned} \tag{A2}$$

with

$$\begin{aligned} I'_{(\eta_1 - f_1)}(0^\circ) &= T[I + (\eta_1 - f_1)\cos 2(0^\circ - \alpha_1)Q \\ &\quad + (\eta_1 - f_1)\sin 2(0^\circ - \alpha_1)U] \\ I'_{(\eta_2 - f_2)}(60^\circ) &= T[I + (\eta_2 - f_2)\cos 2(60^\circ - \alpha_2)Q \\ &\quad + (\eta_2 - f_2)\sin 2(60^\circ - \alpha_2)U] \\ I'_{(\eta_3 - f_3)}(120^\circ) &= T[I + (\eta_3 - f_3)\cos 2(120^\circ - \alpha_3)Q \\ &\quad + (\eta_3 - f_3)\sin 2(120^\circ - \alpha_3)U]. \end{aligned} \tag{A3}$$

Similarly,

$$\begin{aligned} \Delta_{\alpha 0} &= |I'(0^\circ - \alpha_1 + e_1) - I'(0^\circ)| \\ \Delta_{\alpha 60} &= |I'(60^\circ - \alpha_2 + e_2) - I'(60^\circ)| \\ \Delta_{\alpha 120} &= |I'(120^\circ - \alpha_3 + e_3) - I'(120^\circ)|, \end{aligned} \tag{A4}$$

with

$$\begin{aligned} I'(0^\circ - \alpha_1 + e_1) &= T[I + \eta_1 \cos 2(0^\circ - \alpha_1 + e_1)Q \\ &\quad + \eta_1 \sin 2(0^\circ - \alpha_1 + e_1)U] \\ I'(60^\circ - \alpha_2 + e_2) &= T[I + \eta_2 \cos 2(60^\circ - \alpha_2 + e_2)Q \\ &\quad + \eta_2 \sin 2(60^\circ - \alpha_2 + e_2)U] \\ I'(120^\circ - \alpha_3 + e_3) &= T[I + \eta_3 \cos 2(120^\circ - \alpha_3 + e_3)Q \\ &\quad + \eta_3 \sin 2(120^\circ - \alpha_3 + e_3)U]. \end{aligned} \tag{A5}$$

The inverse Mueller matrix of $\mathbf{M}_\mathrm{p}$ is expressed as

$$\mathbf{Z} = \mathbf{M}_\mathrm{p}^{-1} = \frac{1}{T} \begin{pmatrix} z_{11} & z_{12} & z_{13} \\ z_{21} & z_{22} & z_{23} \\ z_{31} & z_{32} & z_{33} \end{pmatrix}. \tag{A6}$$

Then, the uncertainties of the Stokes parameters *I, Q*, and *U* are given by [18]

$$\begin{aligned} \Delta I &= |z_{11}|\left(\Delta_{\eta 0} + \Delta_{\alpha 0}\right) + |z_{12}|\left(\Delta_{\eta 60} + \Delta_{\alpha 60}\right) + |z_{13}|\left(\Delta_{\eta 120} + \Delta_{\alpha 120}\right) \\ \Delta Q &= |z_{21}|\left(\Delta_{\eta 0} + \Delta_{\alpha 0}\right) + |z_{22}|\left(\Delta_{\eta 60} + \Delta_{\alpha 60}\right) + |z_{23}|\left(\Delta_{\eta 120} + \Delta_{\alpha 120}\right) \\ \Delta U &= |z_{31}|\left(\Delta_{\eta 0} + \Delta_{\alpha 0}\right) + |z_{32}|\left(\Delta_{\eta 60} + \Delta_{\alpha 60}\right) + |z_{33}|\left(\Delta_{\eta 120} + \Delta_{\alpha 120}\right). \end{aligned} \tag{A7}$$

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jqsrt.2018.01.013.

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